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Responding to Climate Change: Participatory Evaluation of Adaptation Options for Key Marine Fisheries in Australia's South East

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Planned adaptation to climate impacts and subsequent vulnerabilities will necessarily interact with autonomous responses enabled within existing fisheries management processes and initiated by the harvest and post-harvest components of fishing industries. Optimal adaptation options are those which enable negative effects to be mitigated and opportunities that arise to be maximized, both in relation to specific climate-driven changes and the broader fisheries system. We developed a two-step participatory approach to evaluating adaption options for key fisheries in the fast-warming hotspot of south-eastern Australia. Four fisheries (southern rock lobster, abalone, snapper, and blue grenadier) were selected as case studies on the basis of their high to moderate vulnerability to climatic effects on species distribution and abundance. Involved stakeholders undertook a "first pass" screening assessment of options, by characterizing and then evaluating options. In the characterization step potential adaptation options for each fishery, contextualized by prior knowledge of each species' climate change exposure and sensitivity, were described using a characterization matrix. This matrix included: the specific climate vulnerability/challenges, the implications of each option on the fishery system as a whole, the temporal and spatial scales of implementation processes, and realized benefits and costs. In the evaluation step, semi-quantitative evaluation of options was undertaken by stakeholders scoring the anticipated performance of an option against a pre-determined set of criteria relating to perceived feasibility, risk (inclusive of potential costs), and benefit. Reduction of the total annual commercial catch as well as reductions in both effort and catch through spatial and temporal closures were the options scored as having the highest level of expected benefit and of feasibility and the lowest level of risk of negative outcomes overall. Our screening assessment represents a pragmatic approach to evaluate and compare support for and the effects of alternative adaptation options prior to committing to more detailed formal and resource intensive evaluation or implementation.

Keywords: adaptation options, climate change, commercial fisheries, evaluation, participation

INTRODUCTION

Climate-driven changes in the productivity and distribution of marine fish stocks targeted for commercial use are being observed and predicted globally (Cheung et al., 2009, 2010; Hiddink et al., 2015; Weatherdon et al., 2016). Secondary effects in fisheries in the form of changing fleet dynamics, fishing location choices, gear deployment, targeting and discarding behaviors, supplies to market and ultimately, social and economic returns from these fisheries, are increasingly evident (Michael et al., 2017; Senapati and Gupta, 2017; Stoeckl et al., 2017). This is particularly the case in marine warming "hot spot" areas (Dulvy et al., 2008; Pecl et al., 2014a; Caputi et al., 2016), such as Australia's south-eastern marine region where exposure to climate-driven changes and sensitivity, for a number of species, is high (Pecl et al., 2014c, 2019; Champion et al., 2019).

Planned responses to reduce the vulnerability of commercially important fish stocks and associated fisheries include increasing the resilience of fish stocks to the ecological effects of climate-driven changes and to fishing pressures (Szuwalski and Hollowed, 2016; Pratchett et al., 2017; Le Bris et al., 2018), as well as increasing the adaptive capacity of fishing industries and management systems to adjust to secondary effects of changing productivity and distribution (Aguilera et al., 2015). Such responses may vary in timeframe, spatial extent, degrees of change, and level of state agency or private actor involvement (Miller et al., 2018; Pecl et al., 2019). Hence, responses span both public domains (i.e., public agency management of fisheries) and private interest domains (i.e., recreational and commercial fishery industries) and highlight the complex system properties of fisheries (Lehuta et al., 2016; Selim et al., 2016) and the need to apply a broader governance framework in order to optimize outcomes of adaptation responses (Dutra et al., 2019).

Coordinating adaptive responses across this spectrum of decision and action domains is an increasing requirement of fisheries management and marine governance more broadly. "Mainstreaming" the full array of planned adaptation responses requires that both non-state (i.e., resource-user)-led and public management agency-led adaptation responses are evaluated for their robustness to uncertainty, their capacity to achieve management objectives (Jennings et al., 2016) and the potential for unintended knock on effects (including those leading to maladaptation). Additional planning and assessment processes are necessary for enabling adaptation pathways for managed fisheries (Plaganyi et al., 2011; Leith et al., 2013; Lindegren and Brander, 2018). Mechanistically, these processes include multiple, and potentially iterative, stages of description and evaluation of climate challenges and adaptation options prior to selection and implementation (see **Figure 1**, which incorporates Moser and Ekstrom's (2010) model of adaptation processes). In terms of scope these additional adaptation planning processes require the following:

- A long-term temporal focus to incorporate changing climate effects and the feedback effects of a series of interacting adaptation responses (Wise et al., 2014), as well as transformative options (Kates et al., 2012).
- A social-ecological system conceptual focus to capture the interactions between pressures and primary and secondary responses of the linked ecological and social sub-systems (Leith et al., 2013).
- A multi-stakeholder focus to incorporate a diversity of both public and private sector responses (Miller et al., 2018) and enable co-production of the evaluation of adaptation options by scientists, managers, fishers, and other directly affected stakeholders through participatory and deliberative processes (Stöhr et al., 2014).

Increasingly, integrated assessment frameworks are being developed which incorporate the steps of identifying alternative management options within vulnerability assessments [for example, see Brugère and De Young (2015)]. However, these frameworks have not included formative evaluation of identified options or sets of alternatives. Within the body of adaptation science, a limited number of empirical studies involving forecast assessments of adaptation response options aiming to addressing climate vulnerability in fisheries have been undertaken [examples include: Koehn et al. (2011), Fleming et al. (2014), Pratchett et al. (2017), Blair and Momtaz (2018), Miller et al. (2018), and Young et al. (2019)]. The range of analytical methods applied to assess adaptation options for fisheries includes:

- Qualitative criteria-based assessment, in which criteria are typically normative and drawn from social-ecological systems resilience framework and assessment is based on categorical scoring, such as presence/absence – for example, see Ojea et al. (2017).
- Semi-quantitative criteria-based assessment, in which criteria are more typical of those used in formative evaluation techniques, such as feasibility and risk, and assessment is based on ordinal scoring of criteria (i.e., ranking or Likert scale) – for example, see Marshall et al. (2010).
- Quantitative, model-based simulation of a candidate management option to compare effectiveness at achieving management objectives, such as management strategy evaluation (MSE) – for example, see Castillo-Jordán et al. (2019).

Criteria used in qualitative and semi-quantitative assessments of adaptation options for social-ecological systems are typically highly generic (**Supplementary Table S1**) but specific measurement criteria concerned with spatial, temporal, and governance characteristics of adaptation options are not precluded. Quantitative assessments are resource-intensive – precluding assessment of multiple options or more transformative options – and limited to those options which are state agency-led and directed at achieving current fisheries management targets. Reliance on these evaluative methods alone for adaptation planning risks missing opportunities for optimal adaptation outcomes.

In this paper we describe a "first pass" method based on rapid assessment procedures (Beebe, 1995; Pecl et al., 2014c) which was developed to screen potential adaptation options for responding to vulnerability in marine species targeted

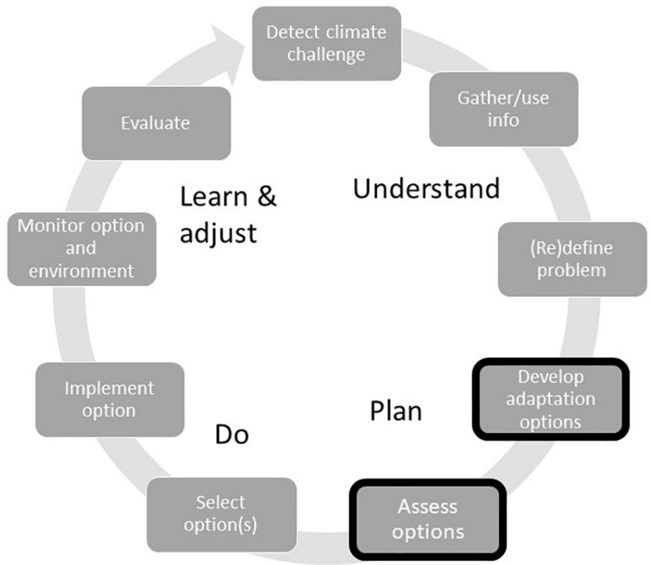

FIGURE 1 | Phases and subprocesses throughout the adaptation process [adapted from Moser and Ekstrom (2010): 22027)] as they apply to the fisheries adaptative management cycle. Highlighted boxes refer to the subprocesses the reported study addresses.

by commercial and recreational fishers. Preferred adaptation options can then be further evaluated using empirical or model-based methods. The two-step method draws on available risk or vulnerability assessments for the initial characterization stage and involves expert-informed semi-quantitative evaluation with key stakeholders from fisheries management agencies, industry, and science organizations. In a second step, semi-quantitative evaluation of options is undertaken by stakeholders scoring the anticipated performance of an option against a pre-determined set of criteria relating to perceived feasibility, risk (inclusive of potential costs) and benefit. The approach was designed to allow comparison of the relative preferences for alternative options between stakeholder groups (fisheries management agencies, industry and science organizations); and support social learning by participants through co-production and review of evaluations (Berkes, 2009; Leith et al., 2013). We report on the application of this method to four case study fisheries and assess the extent to which the method provides a pragmatic solution to the need to *ex ante* evaluate and compare the effects of a potentially large number of alternative responses of fisheries to climate driven changes.

We developed and tested this method as part of a larger study (Pecl et al., 2014b) in which current and expected key climate impacts were identified for four highly targeted marine species in south-eastern Australia. Climate driven challenges, barriers to adaptation, and adaptation options were elicited from industry and management agency experts. The four fisheries investigated were abalone (*Haliotis rubra and Haliotis laevigata*), blue grenadier (*Macruronus novaezelandiaei)*, snapper (*Chrysophrys auratus)*, and southern rock lobster (*Jasus edwardsii)*. In the broader study, results of a rapid biological sensitivity assessment (Pecl et al., 2014c) of the relative risk to climate change impacts on the four selected fisheries species were combined with data obtained through participatory and expert elicitation methods to identify likely key effects of climate change (see summaries of these effects in **Boxes 1–4**).

The south-eastern Australia region is a global marine warming hot spot (Hobday and Pecl, 2013; Caputi et al., 2016). The availability of early observations of climate-driven oceanic and biological change coupled with a history of planned adaptation and supporting stakeholder networks make such regions ideal cases for research to guide management in other locations (Frusher et al., 2014). Ocean warming over recent decades has been considerable (Hobday and Pecl, 2013), and the oceanography of the region is complex, with changes in the physical environment likely to be heterogeneous within the region (e.g., different between the eastern and southern coasts). Fisheries in south-eastern Australia are based on a wide range of species and involve a diversity of fishing methods; fisheries resources are utilized by commercial, recreational and Indigenous stakeholder groups leading to complex social considerations associated with resource access and equity. There are five marine jurisdictions within the region (four States and the Commonwealth) with different environmental and fisheries management legislation and systems; consequently, jurisdictional and political issues may complicate adaption. While species- and population-level responses and secondary effects vary markedly as a result of climate change, commonly occurring responses are evident: changed productivity; changed availability; disease expression; changed product quality; altered habitats; altered weather patterns; acidification; and indirect effects arising from changed availability of co-occurring target species. These properties provide optimal conditions for testing the "first pass" method developed.

BOX 1 | Summary of climate change impacts on abalone fisheries in south-eastern Australia (Pecl et al., 2014b).
Abalone have limited ability to cope with high water temperatures and increased acidification. Of the two key species caught in south-eastern Australia, blacklip (*Haliotis rubra*) prefer lower water temperatures and have lower thermal tolerances than greenlip (*Haliotis laevigata*). Abalone at locations with higher summer water temperatures have lower sizes at maturity and smaller maximum sizes than abalone at locations with cooler summer water temperatures. For blacklip, warmer water temperatures during summer were typically associated with lower blacklip catches (however, there were exceptions to this pattern). Relationships between greenlip catches and the oceanographic variables considered in this study were weaker than those for blacklip, but the general trend was for larger greenlip catches to have been obtained from areas with (1) slower tidal flow rates; and (2) relatively stable water temperatures with a low incidence of high summer, cold summer and cold winter temperatures. Greenlip catches have been smallest in areas with intense and lengthy summers and winters.
Determining the extent to which climate change may influence the Australian abalone stocks was challenging. However, abalone stocks and fisheries are likely to be influenced by three elements of climate change: (1) gradual increases in water temperature and ocean acidification; (2) increased frequency and magnitude of extreme events (e.g., marine heatwaves); and (3) range shifts and altered recruitment and growth rates of competitors and predators (e.g., range expansion of the long-spined sea urchin *Centrostephanus rodgersii)*. Collectively these changes are likely to result in reduced productivity and catches.
Summary:

- For blacklip abalone, the most likely outcome will be a reduction in total production – but with these changes being variable across space, less clear for greenlip abalone.
- Increased water temperatures likely to reduce larval development period, resulting in increased survival and decreased dispersal for both blacklip and greenlip abalone.
- Acidification may negatively affect the development of larvae, if they are unable to adapt to changes in pH.
- Increased acidification could reduce the availability of crustose coralline substrates for larval settlement and early development.
- Range shifts, altered recruitment and altered growth rates of competitors and predators likely to influence abalone production, in part through altered habitats.
- Increased frequency and magnitude of extreme events (e.g., marine heatwaves).

BOX 2 | Summary of climate change impacts on the blue grenadier fishery in south-eastern Australia (Pecl et al., 2014b).
The study involved an extensive review of current knowledge of the location and timing of spawning, larval life history and recruitment of blue grenadier because the production dynamics of this fishery are characterized by extreme variations in year class strength.
Analyses indicated a positive relationship between recruitment strength and wind strength in the autumn (i.e., just prior to the winter spawning period), and a negative relationship between recruitment strength and sea surface temperature during July to November (i.e., the spawning and larval development period in surface waters).
Predicted increases in sea surface temperature off western Tasmania may therefore have a long-term negative impact on average recruitment, while changes to the dynamics of wind strengths, although less certain from prediction models, could influence recruitment dynamics. Preliminary investigation of the link between recruitment dynamics and larval dispersal patterns (i.e., offshore vs. inshore dispersal/retention) also suggested that larval dispersal trajectories are likely an important influence on recruitment dynamics.
Climate change may influence recruitment dynamics of blue grenadier in uncertain ways. The performance of the current harvest control rule to various simulated scenarios of recruitment dynamics was tested. Importantly, the current harvest control rule proved suitable for preventing stock collapse under a range of recruitment dynamics. But the impact on stability/uncertainty of harvests and associated fishery economics was not formally evaluated.
Summary:

- Fishery characterized by highly variable recruitment.
- Recruitment success correlated with windy periods during autumn that create greater vertical mixing and cooler winter-spring Sea Surface Temperatures (SSTs).
- Relationship between oceanographic variables and other factors influencing productivity such as growth, mortality and migration largely unknown.
- Larval dispersal dynamics appears to be an important component of recruitment success.
- Potential negative effects on recruitment and therefore productivity.
- Potential change in dispersal patterns in relation to climate change is unknown; oceanographic projection models currently being developed may provide a useful tool for better understanding of potential changes.
- Increased SST poses greatest risk of the predicted changes through potential negative impacts on egg/larval development and survival.

MATERIALS AND METHODS

Data collection and preliminary descriptive analysis of results at the case study level were undertaken and reported as part of the larger study, *Preparing fisheries for climate change: identifying adaptation options for four key fisheries in South Eastern Australia* (see Pecl et al., 2014b for further details). Characterization and evaluation exercises were conducted at a series of stakeholder workshops held across 2012 and 2013. Stakeholders were members of the advisory or management communities for the four case study fisheries. This included policy and management staff from fisheries management agencies, research scientists, and commercial and recreational fisher representatives. Recruitment of committee members as participants in the characterization and evaluation of options activities was undertaken on the basis that the membership of the committees included a range of direct stakeholder groups (i.e., fishing representatives, policy and management agency staff, and fishery assessment scientists). In addition, the role of the committees was to consider adoption of the outcomes of the study as part of their broader function to provide advice to decision makers on options for managing the fishery and undertake any agreed co-management activities. Ethics approval was not required as participants were aged 18 or older and public representatives appointed to a Management/Fishery Advisory Committee. All workshop activities were conducted as activities within advisory committee meetings, which were administered by the fisheries management agencies in each case. This was consistent with the UTAS Social Sciences Human Research Ethics Committee's application of the Australian Code for the Responsible Conduct of Research. Workshop participants were informed of the characterization and evaluation activities prior to them taking place through the communication mechanisms used for the relevant committees, and then on the day prior to the activities themselves. Committee members were provided with the option to not participate prior to the characterization and evaluation activities taking place. Consent was therefore inferred from participant's decision to participate.

BOX 3 | Summary of climate change impacts on snapper fisheries in south-eastern Australia (Pecl et al., 2014b).

Throughout the broad latitudinal range of snapper around the Australian continental shelf, temperatures between 18 and 22°C were consistently identified as the optimal for spawning and survival of snapper eggs and larvae. Forecast modeling was conducted to assess how this optimal temperature window may change under climate change over the next 50 years.

There is high regional variability in predicted availability of water temperature is suitable for snapper spawning relative to historical patterns, or changes to the timing and/or length of periods of optimal spawning temperatures. While spawning behavior is intimately linked to water temperature regimes, the survival of the larvae and juveniles appears to be related to different climatic factors in different areas.

An additional set of factors in some regions are river flow and associated nutrient input regimes and plankton food chain dynamics, which in these regions are more critical in influencing larval survival rates and juvenile recruitment than water temperature alone. While changes to the overall time period of optimal spawning temperature are predicted to be minimal in these regions, there will be significant changes to the timing and continuity of the optimal period. This may affect migratory dynamics and will have important consequences for how spawning timing overlaps with the optimal periods of prey availability for the planktonic larval stages, with uncertain implications for recruitment dynamics.

Summary:

- Population dynamics strongly driven by inter-annual variation in recruitment.
- Interactions between SST dynamics and plankton productivity thought to affect recruitment success; however, there is no simple environmental/climatic relationship that is consistent across the broad geographic range.
- Predicted temperature increases likely to create adverse conditions for spawning/larval survivorship
- Predicted SSTs through central and southern New South Wales, Victoria (excluding Port Phillip Bay) as well as the northern and eastern waters of Tasmania will increase the period of optimal spawning conditions facilitating southern range extension and consolidation.
- Abundance and distribution changes to predators, competitors and prey will be key ecosystem factors affecting snapper. These may be positive or negative and are likely to vary across distribution.
- Current projected changes to weather patterns are not considered specific enough to predict impacts on access to open coastal water fishing areas, although the impacts are likely to be limited for sheltered water fisheries.
- Climate change predicted to reduce optimal conditions for spawning and larval survival in warmer areas and provide increased opportunities in south-eastern Australia, particularly northern and eastern Tasmania.
- Climate change likely to alter existing recruitment variability due to changes in SSTs and nutrient supply dynamics which are not currently well understood.

Potential adaptation options were identified at an initial workshop held for the four fisheries in March 2012 which involved 40 stakeholders from the combined committees [see Pecl et al. (2014b) for further details]. The initial list of adaptation options for each fishery was then reviewed and revised by members of the project team specializing in each case study fishery to reduce any redundancies or duplication and to link individual options to the specific climate challenges they addressed. The revised options for each fishery were validated with stakeholders participating in the characterization and evaluation activities for that fishery case study. This validation was undertaken via out-of-session committee procedures prior to the second and third rounds of workshop activities, held for each fishery case study throughout 2013 in conjunction with advisory committee meetings (Pecl et al., 2014b).

BOX 4 | Summary of climate change impacts on southern rock lobster fisheries in south-eastern Australia (Pecl et al., 2014b).

The study examined the effects of environmental variables on southern rock lobster (*Jasus edwardsii*) puerulus settlement across South Australia, Victoria and Tasmania, at monthly and annual scales. Monthly investigations aimed to identify environmental signals immediately prior to settlement while the annual analyses acknowledged the long planktonic larval phase (~1 year).

There were no clear signals between environmental variables (current, wind speed, temperature and rainfall) and monthly puerulus settlement. However, within specific regions, signals were identified at the annual scale.

Overall, the results highlighted a number of environmental variables that impacted on settlement but these varied regionally. In addition, the explanatory strength of these variables was not strong, suggesting that other unknown processes also impact on settlement. As a result, it is difficult to predict the impact of climate change on rock lobster fisheries. However, given that puerulus settlement is highly variable between years, the impact of recruitment variability is important in relation to potential climate change scenarios.

Summary:

- Juveniles and adults live on rocky reef in a wide range of different marine communities.
- Climate change can potentially affect recruitment by altering patterns of larval dispersal and survival.
- Climate change effects more likely to impact recruitment during the larval development phase.
- A number of environmental variables impacted on settlement, but these varied regionally.
- Predicting impact of climate change is difficult, however, puerulus settlement is influenced by a complex set of environmental factors that expose the fishery to risks resulting from climate change.
- Climate change impacts likely to affect rock lobster predator/prey relationships.
- Increased rock lobster mortality through octopus predation has been identified during years with higher average water temperatures.

Characterization of Options

The objective of the second workshop activity in 2013 was to characterize adaptation options for each case study fishery. The purpose of the characterization exercise was to describe those characteristics which needed to be considered in the evaluation of the perceived risks, benefits and feasibility of each option, and in decision-making processes for fisheries more broadly. Adaptation options were analyzed during these activities using the purpose-designed adaptation characterization matrix (**Table 1**).

The characterization matrix was developed by the broader project's scientific working group on the basis of a review of typologies of adaptation responses to climate driven effects. Typologies included those developed on the basis of both empirically observed adaptation responses (Biagini et al., 2014) and conceptual frameworks for identifying types of adaptation options in planning exercises [for example, the resilience framework (Nelson et al., 2007) and the Exposure-Sensitivity-Adaptive Capacity assessment framework (IPCC,, 2007)]. Commonly used characteristics include the domain of adaptation activity (Biagini et al., 2014); the goal of adaptation; the degree of intent and planning

TABLE 1 | Characterization matrix used to identify the key attributes of adaptation options to specific climate-driven challenges.

Characteristic	Typology/Score
Degree of adaptation	• Autonomous (i.e., within range of existing adjustment responses by operators or managers, not requiring any collective or institutional change or approval) • Business-as-(mostly)-usual (i.e., a minor adjustment to an existing management or industry strategy) • Incremental • Transformative
Implementation	
Scale of application	National, State, Zone, Sub-zone
Jurisdiction/s	State, territory, or commonwealth
Significance of difference between jurisdictions	Low, medium, high
Lead time to implementation	<1 year, 1–5 years, >5 years
Who implements	Management, industry, research, multiple
Additional cost	Nil, low, medium, high
Who pays	Industry, government, consumers, post-harvest, local coastal communities
Level of controversy	Low, medium, high
Benefits	
Primary beneficiary	Fishers, fishery, fish stock, ecosystem
Scale of benefit	National, state, zone, sub-zone
Consequence period after implementation	<1 year, 1–5 years, >5 years
Addresses other climate challenges	List other challenges
Barriers	Individual barriers listed

Sources: *Lebel et al. (2006), Grafton (2010), Miller et al. (2010), Stafford Smith et al. (2011), and Wise et al. (2014).*

(Fankhauser et al., 1999; Adger et al., 2005; Grüneis et al., 2016); the type of agent and level of agency (Tompkins and Eakin, 2012; Sova et al., 2014; Bradley and Steele, 2015; Pecl et al., 2019); the degree of system change the adaptation would produce (Stafford Smith et al., 2011; Mushtaq, 2018); and the extent of path dependency between adaptation responses (Haasnoot et al., 2013; Wise et al., 2014; see **Supplementary Table S2**).

The degree of adaptation presented by an option was incorporated in the matrix by developing the following typology: Autonomous (i.e., options already within the range of existing adjustment responses by operators or managers, and not requiring any collective or institutional change or approval to implement); Business-as-(mostly)-usual (i.e., a minor adjustment to an existing management or industry strategy); Incremental (i.e., a major adjustment to an existing management or industry strategy but not a change to fundamental attributes); and, Transformative (i.e., a change to fundamental attributes or results in irreversible regime change of a system) (Stafford Smith et al., 2011; Mushtaq, 2018). A further characteristic, "Primary implementation stakeholder," was constructed in the data analysis stage based on a synthesis of the way in which implementation of an adaptation option was described under the "Who pays" and "Barriers" characteristics (**Table 1**).

The characterization matrix was circulated to participants prior to the second round of workshops, and then populated for each fishery with participants at the workshops. Descriptive statistical analysis was used to determine the proportion of adaptation options deemed to have specific characteristics.

Evaluation of Options

Semi-quantitative evaluation of adaptation options was undertaken by the same participants in the third round of workshop activities held in late 2013 by scoring the anticipated performance/outcome of an adaptation option against a pre-determined set of normative criteria and related indicators. Candidate criteria and indicators were identified on the basis of the review of literature (**Supplementary Table S2**). Criteria were then selected and refined for the fishery-specific context at a technical workshop in August 2013 with input from the broader project's scientific working group (**Table 2**). The three major evaluation axes selected were: Feasibility, Risk and Expected benefits [after Prober et al. (2011)]. A numeric rating scale was used to score indicators for each criterion (Colman et al., 1997). Participants in the third round of workshops collectively discussed then individually scored options on a scale of 1–5 for each indicator, where 1 = Less Feasible/Low Risk/Low Expected benefits and 5 = More Feasible/High Risk/High Expected benefits.

Evaluation was undertaken for all options for each fishery, however, evaluation results which could be used in the analysis were available for only a sub-set of options. Response rates were low for a number of options and for a number of fisheries due to the decision by some stakeholders to not evaluate their least preferred options and to low numbers of attendees at the committee meetings for some fisheries. Options with less than two responses for any of the stakeholder groups were deemed not suitable for further analysis in the study and excluded. Responses of "N/A" were treated as a non-score for the purposes of analysis. If more than one third of responses for a given indicator were N/A then the "Consensus" level was deemed to be "Unsatisfactory." Evaluation classes were developed for classification and interpretation of the results when combined and averaged for each stakeholder group (**Table 2**) and the results for each comprehensively evaluated option for each fishery were plotted for comparison.

Results were collated and analyzed by averaging the scores given by respondents for a given option for each indicator. Scores of all workshop participants and of respondents of a specific stakeholder group (i.e., fishing industry, managing agencies) were calculated to generate both a combined mean score and a mean score for each stakeholder group for each criterion. Results of the analysis of the evaluated options for each fishery were then compared to determine the extent of variation in the levels of assessed feasibility, risk, and expected benefits. This was undertaken to appraise the extent to which the evaluation criteria and assessment

TABLE 2 | The three major evaluation criteria selected: feasibility, risk, and expected benefits.

Criteria	Scoring system	Score range	Mean evaluation score class
1. Feasibility			
1.1. Cost of implementation	1 – 5, Lower score = less feasible, Higher score = more feasible	0.1–1.0	Negligible feasibility
1.2. Ongoing cost		1.1–2.0	Very low feasibility
1.3. Legal and procedural barriers		2.1–3.0	Low feasibility
1.4. Social and political barriers		3.1–4.0	Moderate feasibility
1.5. Need for additional skills, knowledge and expertise		4.1–5.0	High feasibility
2. Risk			
2.1 Failing to address climate challenge	1 – 5, Lower score = lower level of risk, Higher score = higher level of risk	0.1–1.0	No risk
2.2 Negative impact of action on biological sustainability of fish stock		1.1–2.0	Very low risk
2.3 Negative impact on wider ecosystem		2.1–3.0	Low risk
2.4 Reduced economic sustainability of the fishery		3.1–4.0	Moderate risk
2.5 Reduced fisher profit		4.1–5.0	High risk
2.6 Reduced employment			
2.7 Reduced social license to operate			
2.8 Limiting other adaptation options			
3. Expected benefits			
3.1 Benefit to biological sustainability of fish stock	1 – 5, Lower score = lower level of expected benefit, Higher score = higher level of expected benefit	0.1–1.0	No expected benefit
3.2 Benefit to wider ecosystem		1.1–2.0	Very low expected benefit
3.3 Benefit to economic sustainability of fishery		2.1–3.0	Low expected benefit
3.4 Benefit to fisher profit		3.1–4.0	Moderate expected benefit
3.5 Benefit to employment		4.1–5.0	High expected benefit
3.6 Benefit to overall fisheries management			
3.7 Benefit after implementation			

A numeric rating scale was used to score indicators for each criterion evaluation classes were developed for interpretation of the results.

rubric were sensitive to the different attributes of the options being evaluated. A summary analysis was also undertaken to compare the overall extent to which different stakeholder groups view various types of adaptation options by comparing the percentage of respondents from each stakeholder group who scored different evaluation classes for each type of option.

Analysis of the level of consensus between all respondents within and between stakeholder groups, as well as collectively, was undertaken by determining the percentage of scores for an evaluated adaptation option and criterion in each evaluation class. The following categories of consensus were used [after Lemieux and Scott (2011)]: High = 70% of responses in one evaluation class or 80% in two adjacent classes (i.e., "low" and "very low"); Medium = 60% of responses in one evaluation class or 70% in two adjacent classes; Low = 50% of responses in one evaluation class or 60% in two adjacent classes; and, None = Less than 60% of responses in two adjacent evaluation classes.

RESULTS

Across the four fisheries 100 adaptation options were identified to address the vulnerability arising from the following broad climate challenges: changed productivity; changed availability; disease expression; changed product quality; altered habitats; altered weather patterns; acidification; and indirect effects arising from changed availability of co-occurring target species (**Table 3**).

Characterization of Adaptation Options by Fishery

Climate challenges and associated adaptation options identified across the four fisheries reflected the specific drivers of climate vulnerability identified for each fishery as part of early stages of the project (see **Boxes 1–4**). For example, abalone as a sessile species is comparatively more exposed to higher rates of mortality associated with marine heatwave events and was the only species to specify productivity change due to mortality from thermal shock as a climate challenge (see **Table 3A**, climate challenge 1 and options 1a–1e). Reduced productivity from a broad range of drivers was identified as a climate challenge for all four fisheries (**Tables 3B–D**) however, for the snapper fishery, increased productivity was also identified due to a southward shift in distribution (**Table 3C**). Increased disease expression was another challenge identified for abalone, blue grenadier and southern rock lobster (**Tables 3A,B,D**) but not for snapper, which may reflect the large geographic range of and number of species (in addition to snapper) within this fishery, reducing its disease exposure.

For all four fisheries, adaptation options ranged from those characterized as autonomous adjustments by industry (2% of the total number of options), as business-as-(mostly)-usual (29%), as incremental (46%), to those characterized as transformative (23%) (**Figure 2**). Options characterized as transformative were identified for a range of broad climate

TABLE 3A | Summary characterization of adaptation options identified for abalone.

Climate Challenge	Specific climate effect	Option no.	Potential adaptation options	Adaptation degree	Primary implementation stakeholder
1. Mortality from thermal shock (extreme events)	1. Locally (e.g., Actaeon Is. 2010)	1a	Reduce Total Allowable Commercial Catch, or TACC (by for example 30–40%)*	Business-as-(mostly)-usual	Management
	2. Regionally (e.g., South Australia Southern Zone 2013)	1b	Spatial management – catch controls	Incremental	Management
		1c	When forecast, bring harvest forward*	Transformative	Management
		1d	Closed season (within annual season)	Incremental	Management
		1e	Stock enhancement – selective breeding for thermal resistance	Transformative	Industry
2. Reduced productivity	1. Locally (block/area level)	2a	Reduce TACC (by for example 30–40%)	Business-as-(mostly)-usual	Management
	2. Regionally (zone level)	2b	Spatial management – catch controls	Incremental	Management
		2c	Review Harvest strategy	Business-as-(mostly)-usual	Management
		2d	Stock enhancement – selective breeding for thermal resistance	Transformative	Industry
		2e	Translocation	Transformative	Industry
3. Biological changes	1. Changes in size at maturity	3a	Periodic review of biological parameters	Business-as-(mostly)-usual	Management
	2. Changes in growth rate, max size and weight	3b	Spatial management – variable Minimum Legal Lengths, or MLLs, and catch controls	Incremental	Management
	3. Changed time period from size at maturity to MLL	3c	Review Harvest strategy	Business-as-(mostly)-usual	Management
	3. Spatial and/or temporal recruitment changes	3d	Reduce TACC (by for example 30–40%)	Business-as-(mostly)-usual	Management
		3e	Closed season (within annual season)	Incremental	Management
4. Disease expression	1. *Perkinsus*	4a	Design comprehensive biosecurity system	Incremental	Management
	2. Abalone Viral Ganglioneuritis or AVG	4b	Stock enhancement – selective breeding for disease resistance	Transformative	Industry
	3. Algal blooms	4c	Closed season (within annual season)	Incremental	Management
		4d	Spatial management – variable MLLs and catch controls	Incremental	Management
		4e	Reduce TACC (by for example 30–40%)	Business-as-(mostly)-usual	Management
5. Product quality	1. Changed product characteristics	5a	Alter handling practices, including timing of fishing	Incremental	Industry
		5b	Vary/develop alternate products/markets for greenlip and blacklip	Incremental	Industry
		5c	Closed season (within annual season)	Transformative	Management
6. Altered habitats	1. Changed abundance of predators/competitors	6a	Undertake competitor/predator kills	Transformative	Industry
	2. Changed abundance of preferred algal species	6b	Fishery and product development [e.g., urchin (*Centrostephanus*)]	Transformative	Industry

(Continued)

TABLE 3A | Continued

Climate Challenge	Specific climate effect	Option no.	Potential adaptation options	Adaptation degree	Primary implementation stakeholder
		6c	Reduce TACC (by for example 30–40%)	Business-as-(mostly)-usual	Management
		6d	Spatial management – catch controls	Incremental	Management
		6e	Review Harvest strategy	Business-as-(mostly)-usual	Management
		6f	Habitat enhancement	Transformative	Industry
		6g	Closed season (within annual season)	Incremental	Management
7. Altered weather patterns	1. Changes to wind/swell patterns	7a	Prioritize fishing trips including fleet mobilization*	Incremental	Industry
		7b	Increase use of mother boats*	Incremental	Industry
		7c	Change number of divers*	Transformative	Industry
		7d	Stop fishing to increase biomass (raise catch per unit effort)*	Transformative	Management
		7e	Carry quota across years (Tasmania and Victoria only)*	Transformative	Management
		7f	Flexibility in quota transfers*	Incremental	Management
8. Acidification	1. Changed larval development	8a	Reduce TACC (by for example 30–40%)	Business-as-(mostly)-usual	Management
		8b	Spatial management – variable MLLs and catch controls	Incremental	Management
		8c	Review Harvest strategy	Business-as-(mostly)-usual	Management

*Characteristics included are: climate challenge being addressed; degree of adaptation; and, key implementation stakeholder (inferred from combination of responses to "who pays" and "barriers"). *indicates evaluated options.*

challenges, including: changed productivity; changed availability; disease expression; altered habitats; and altered weather patterns. Transformative options included stock enhancement and development of new fisheries, products and product markets. The abalone fishery had the highest proportion of options characterized as transformative (31%) while in contrast, the southern rock lobster fishery had the lowest proportion (16%).

Implementation was primarily dependent on management agencies for 63% of the total identified options across all fisheries, while for 37% of the options industry was the primary implementation stakeholder. For the abalone fishery, this result differed as only 14% of options were dependent on industry stakeholders for implementation. In contrast, for the southern rock lobster fishery 47% of options were dependent on industry as the primary implementation stakeholder (**Figure 2**). Overall, options characterized as business-as-(mostly)-usual and incremental in terms of degree of adaptation were predominantly dependent on management agencies as primary implementation stakeholders (79% and 63%, respectively). Transformative options were predominately dependent on industry as the primary stakeholder (57%).

The adaptation options identified ranged across all the available categories of temporal and spatial characteristics for all four fisheries. Full results of the characterization of adaptation options are provided in **Supplementary Tables S3A–D**.

Evaluation of Feasibility, Risk, and Benefit by Fishery

For the abalone fishery, eight adaptation options in response to two climate challenges were available for evaluation based on sufficient levels of responses across the three stakeholder groups (**Figure 3A** and **Table 4**). In addressing the challenge of increased mortality from thermal shock, the option of an up to 40% reduction in the Total Allowable Commercial Catch, or TACC, (1a) was scored as having greater expected feasibility and similar level of risk and expected benefit ("high," "low," and "low," respectively) compared to the alternative option. In addressing the climate challenge to the abalone fisheries posed by altered weather patterns, all six adaptation options were scored similarly when responses of all stakeholder groups were combined, with none of the options being ranked above "low" in terms of level of expected benefit (**Figure 3B** and **Table 4**).

For blue grenadier three different adaptation options designed to address the climate risk of reduced productivity and availability (blue grenadier climate challenge 1) were available for evaluation based on sufficient levels of responses across the three stakeholder groups. Reducing the TACC scored highest ("high") in terms of feasibility, while in

TABLE 3B | Summary characterization of adaptation options identified for Blue grenadier.

Climate challenge	Specific climate effect	Option no.	Potential adaptation options	Adaptation degree	Primary implementation stakeholder
1. Changed productivity and/or availability	1. Smaller than anticipated spawning stock biomass, or SSB	1a	Reduce TACC*	Business-as-(mostly)-usual	Management
	2. Changes in recruitment (magnitude, frequency)	1b	Reduce effort	Incremental	Management
		1c	Adapt gear to reduce impact on juveniles	Incremental	Industry
		1d	Improve larval survival	Transformative	Management
		1e	Harvest alternative species	Incremental	Industry
		1f	Temporal or spatial closure for juveniles*	Incremental	Management
		1g	Extend quota period*	Incremental	Management
2. Spawning Biomass Changes	1. Changes in timing of spawning	2a	Improved fish finding technology	Incremental	Industry
	2. Changes in density (spread of SSB)	2b	More smaller vessels to find fish	Transformative	Industry
	3. Changes in location (depth/area)	2c	Shift timing/location of operations	Incremental	Industry
		2d	Spatial management/assessment	Incremental	Management
3. Biological changes	1. Changes in size at maturity	3a	Periodic review of biological parameters	Incremental	Management
	2. Changes in growth	3b	Adapt assessment accordingly	Incremental	Management
4. Disease expression	1. Disease expression	4a	Design comprehensive biosecurity system	Transformative	Management
5. Product quality	1. Changed product characteristics	5a	Alter handling practices, including timing of fishing	Business-as-(mostly)-usual	Industry
		5b	Develop alternate products/markets	Incremental	Industry
6. Altered habitats	1. Changed abundance of predators/competitors/prey	6a	Periodic review of biological parameters	Incremental	Management
		6b	Adapt assessment accordingly	Incremental	Management
		6c	Reduce/increase TACC	Business-as-(mostly)-usual	Management
		6d	Review Harvest strategy	Incremental	Management
7. Altered weather patterns	1. Altered weather patterns	7a	Change frequency/duration of trips	Incremental	Industry

*Characteristics included are: climate challenge being addressed; degree of adaptation; and, key implementation stakeholder (inferred from combination of responses to "who pays" and "barriers"). *indicates evaluated options.*

terms of expected benefit, reducing the TACC and spatial or temporal closures both scored ("moderate") which was above the option of a 2-year quota period ("low") (**Figure 3C** and **Table 4**).

For snapper, the options available for evaluation based on sufficient levels of responses across the three stakeholder groups addressed the climate challenge of reduced productivity and availability (snapper climate challenge 1). The highest scoring adaptation option with regard to the level of expected benefit was to implement single cross-jurisdictional management, which was ranked as "high." However, this option was also ranked the lowest ("very low") in terms of feasibility (**Figure 3D** and **Table 4**). The adaptation option with the next highest level of expected benefit was to change seasonal fishing activities/methods, which was scored as "moderate," however, as with single cross-jurisdictional management this feasibility was scored as "low."

For southern rock lobster, adaptation options to address two climate challenges were available for evaluation based on sufficient levels of responses across the three stakeholder groups; reduced productivity (southern rock lobster climate challenge 1) and altered ecosystem – increased octopus predation (southern rock lobster climate challenge 3). For reduced productivity all three options were scored quite similarly, with all options scoring "moderate" for level of expected benefit. However, in terms of feasibility, reducing the TACC was scored "moderate" with the other options both ranked "low" (**Figure 3E** and **Table 4**). With regard to addressing the challenge of increased octopus-induced mortality, there were two evaluated options. Spatial closures was scored as having a

TABLE 3C | Summary characterization of adaptation options identified for Snapper.

Climate challenge	Specific climate effect	Option no.	Potential adaptation options	Adaptation degree	Primary implementation stakeholder
1. Reduced productivity and availability	1. Northward extension of distribution is reduced	1a	Reduce targeted effort*	Business-as-(mostly)-usual	Management
	2. Timing of peak local abundance changes (local and regional)	1b	Shift fishing operations (regional)*	Incremental	Industry
	3. Negative effects on recruitment	1c	Change target species (local)	Business-as-(mostly)-usual	Industry
		1d	Change seasonal fishing activities/methods*	Incremental	Industry
		1e	Implement single cross-jurisdictional management/access arrangements across stock range (i.e., east stock)*	Transformative	Management
2. Increased productivity and availability	1. Southward shift in distribution – Tasmania	2a	Initiate research/monitoring program: Find out the origin of the new fishery – life history/movement/ecological impact, abundance research	Incremental	Management
		2b	Developmental fishery plan/fishery expansion plan	Business-as-(mostly)-usual	Industry
		2c	Establish new fishery	Transformative	Management
		2d	Implement restrictions (size/bag/gear etc.)	Incremental	Management
		2e	Implement single cross-jurisdictional management/access arrangements across stock range (i.e., east stock)	Transformative	Management
3. Altered habitats	1. Changed abundance of predators/competitors/prey	3a	Reduce fishing effort on snapper	Business-as-(mostly)-usual	Management
		3b	Shift fishing effort to other species	Business-as-(mostly)-usual	Industry
		3c	Alter fishing activities/methods	Incremental	Industry
		3d	Stocking of nursery areas	Transformative	Industry
		3e	Review management (harvest) of prey species	Incremental	Management
		3f	Implement control measures on pest species/new competitors	Incremental	Management
4. Declines in other associated target species	1. Increased targeting of snapper	4a	Reduce fishing effort on snapper	Business-as-(mostly)-usual	Management
		4b	Restrict transfer of effort to snapper	Business-as-(mostly)-usual	Management
5. Altered weather patterns	1. Reduction in freshwater flows	5a	Stocking of nursery areas	Transformative	Industry
	2. Local population decline	5b	Reduce fishing effort on snapper	Business-as-(mostly)-usual	Management
	3. Negative effects on recruitment	5c	Shift fishing effort across species	Business-as-(mostly)-usual	Management

*Characteristics included are: climate challenge being addressed; degree of adaptation; and, key implementation stakeholder (inferred from combination of responses to "who pays" and "barriers"). *indicates evaluated options.*

TABLE 3D | Summary characterization of adaptation options identified for Southern rock lobster.

Climate challenge	Specific climate effect	Option no.	Potential adaptation options	Adaptation degree	Primary implementation stakeholder
1. Change in productivity	1. Negative effects on recruitment	1a	Change/reduce TACC*	Business-as-(mostly)-usual	Management
	2. Timing of peak local abundance changes (local and regional)	1b	Adjust size limits	Incremental	Management
		1c	Seasonal/spatial closures	Business-as-(mostly)-usual	Management
		1d	Alter sector allocations (ie. reduce recreational share of resource)	Incremental	Management
		1e	Translocation*	Transformative	Industry
		1f	Stock enhancement*	Transformative	Industry
2. Biological changes	1. Change in distribution	2a	Finer spatial scale management	Incremental	Management
	2. Changes to timing and synchronicity of molting	2b	Seasonal/spatial closures	Business-as-(mostly)-usual	Management
		2c	Processor setting limits	Transformative	Industry
		2d	Develop holding technology (land based)	Incremental	Industry
3. Altered ecosystems	1. Increase in octopus predation (abundance)	3a	Seasonal/spatial closures to avoid using areas/seasons of high predation*	Business-as-(mostly)-usual	Management
	2. Increased predation/mortality (post release)	3b	Increase the take of octopus (bycatch/dedicated targeting)*	Business-as-(mostly)-usual	Industry
	3. Increase in on-board mortality through increases water temp	3c	Retain discarded species	Incremental	Industry
		3d	Gear technology investment	Autonomous	Industry
4. Disease expression	1. Increased frequency/intensity of toxic algal blooms	4a	Early detection and monitoring	Incremental	Industry
		4b	Spatial/temporal closures	Business-as-(mostly)-usual	Management
5. Altered weather patterns	1. Increase/decrease in suitable fishing days due to weather	5a	Allow multiple licenses on boats	Incremental	Management
		5b	Increase pot limits	Incremental	Management
		5c	Increase vessel size	Autonomous	Industry

*Characteristics included are: climate challenge being addressed; degree of adaptation; and, key implementation stakeholder (inferred from combination of responses to "who pays" and "barriers"). *indicates evaluated options.*

higher benefit, than increased take of octopus (**Figure 3F** and **Table 4**) while its feasibility was scored "moderate" for both and risk "low."

Level of Consensus by Fishery

For the abalone fishery, there was a high level of consensus within and across stakeholder groups for feasibility, risk and level of expected benefit (**Table 4**). The two exceptions to this were, firstly; the option of bringing the harvest forward in response to marine heatwave forecasts, for which the level of combined consensus was low for feasibility and high for level for expected benefit (all stakeholder groups deemed the level of expected benefits to be "low"); and, secondly; the option of increasing the use of mother boats to address the challenge of altered weather patterns, for which the combined consensus level was also low for feasibility but high for risk and level of expected benefit (both of which were scored as "low"). Overall, industry respondents generally scored options as having a lower feasibility and lower expected benefit than management and research respondents.

For blue grenadier, the level of combined consensus across all stakeholder groups was high for feasibility, risk, and benefit for each of the three adaptation options assessed (**Table 4**). This could be explained by the low sample size, or the single jurisdictional management arrangements for this fishery wherein the issues being faced are consistent in terms of management arrangements, industry participant and fleet characteristics, and research programs.

For the snapper fishery, the level of combined consensus was low for the feasibility of two adaptation options designed to reduce effort through spatial or temporal closures (**Table 4**). For

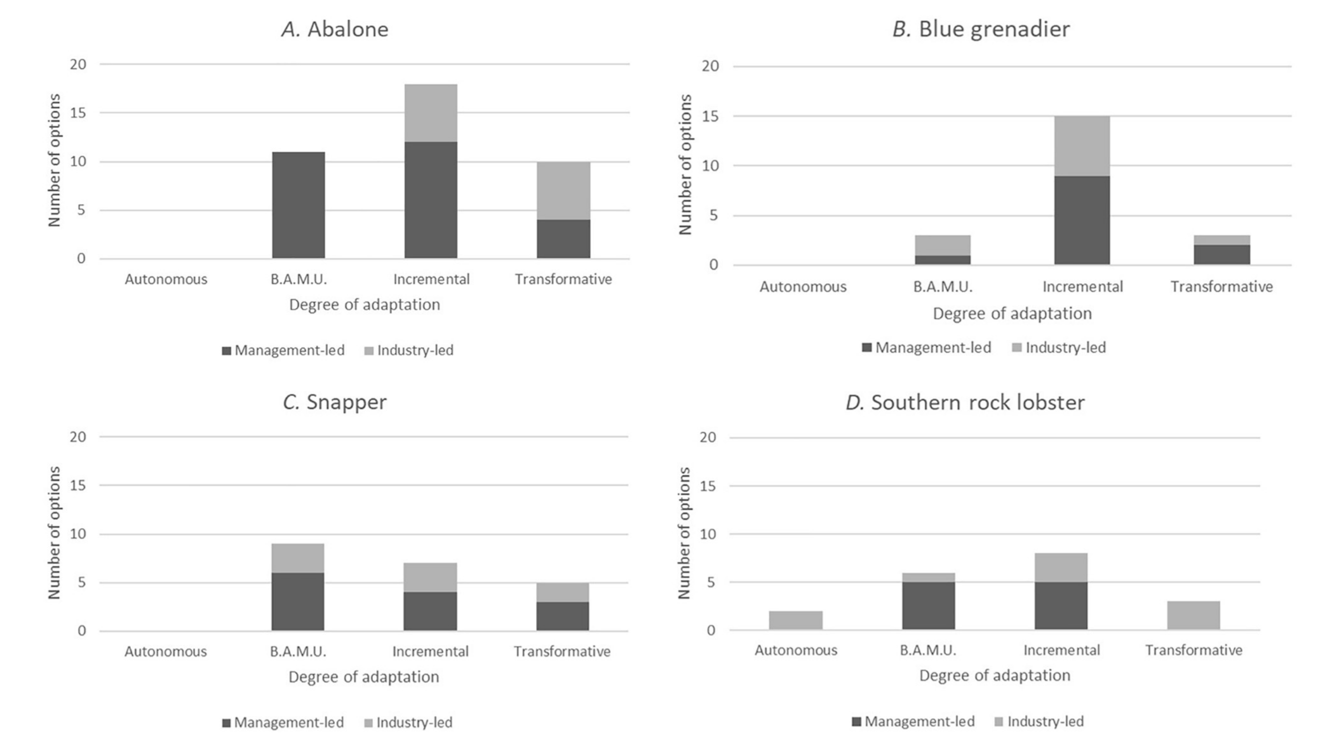

FIGURE 2 | Comparison of number of adaptation options for abalone **(A)**, blue grenadier **(B)**, snapper **(C),** and southern rock lobster **(D)** fisheries in south-eastern Australia by their summary characteristics: degree of adaptation and primary implementation stakeholder.

risk and level of expected benefit the level of combined consensus was either low or moderate for both options also. However, for the options of changing seasonal fishing activities/methods, and implementation single jurisdictional management arrangements, levels of combined consensus were generally medium to high.

For southern rock lobster, the combined consensus levels for feasibility and risk for all five options evaluated was moderate to high overall (**Table 4**). The notable difference in consensus was between the industry, management and research scores for the level of expected benefit of reducing the TACC by up to 40%, translocation and stock enhancement options proposed to address reduction in productivity. For the option of reducing the TACC both research and management respondents scored a "moderate" level of expected benefit, while industry respondents scored the level as "low." In contrast, for translocation and stock enhancement options, research and management respondents considered the benefit to be "low," whilst industry considered the benefit to be "high" and "moderate," respectively.

Summative Evaluation Across Fisheries

For the majority of adaptation options, feasibility was scored at moderate, and risk of negative outcomes and level of expected benefits were scored at low when scores for all stakeholders for each fishery were combined (**Table 4**). Combined scores for feasibility showed the greatest variation (30% of the twenty options were scored low for feasibility, 55% moderate and 10% high). In contrast, combined scores for risk of negative outcomes were low for 85% of the options. Combined scores for level of expected benefits were more widely distributed across the options (65% of options were scored low, 30% moderate).

Comparison of the averaged scores of commonly selected adaptation options across fisheries by the different stakeholder groups found few differences between groups. The option to reduce TACCs by up to 40% was selected for the abalone, blue grenadier and southern rock lobster fisheries. Research and management respondents scored the level of expected benefits from this option as moderate while industry respondents scored it as low (**Figure 4A**). For the same option averaged evaluation classes for feasibility and level of risk of negative outcomes were the same for all stakeholder groups (moderate and low, respectively), indicating higher levels of support for this option from research and management stakeholders overall. The option to extend the quota catching period was selected for the abalone and blue grenadier fisheries. Research and management respondents scored the level of feasibility of this option as moderate while industry respondents scored it as low (**Figure 4B**). For the same option the averaged evaluation class for level of risk of negative outcomes and of expected benefit was low for all stakeholder groups. The option to introduce additional seasonal or temporal closures was selected for the blue grenadier, snapper and southern rock lobster fisheries. Research, management and industry respondent scores of the level of feasibility, risk of negative outcomes and of expected benefit were the same for all groups (moderate, low, and moderate, respectively) for this option (**Figure 4C**).

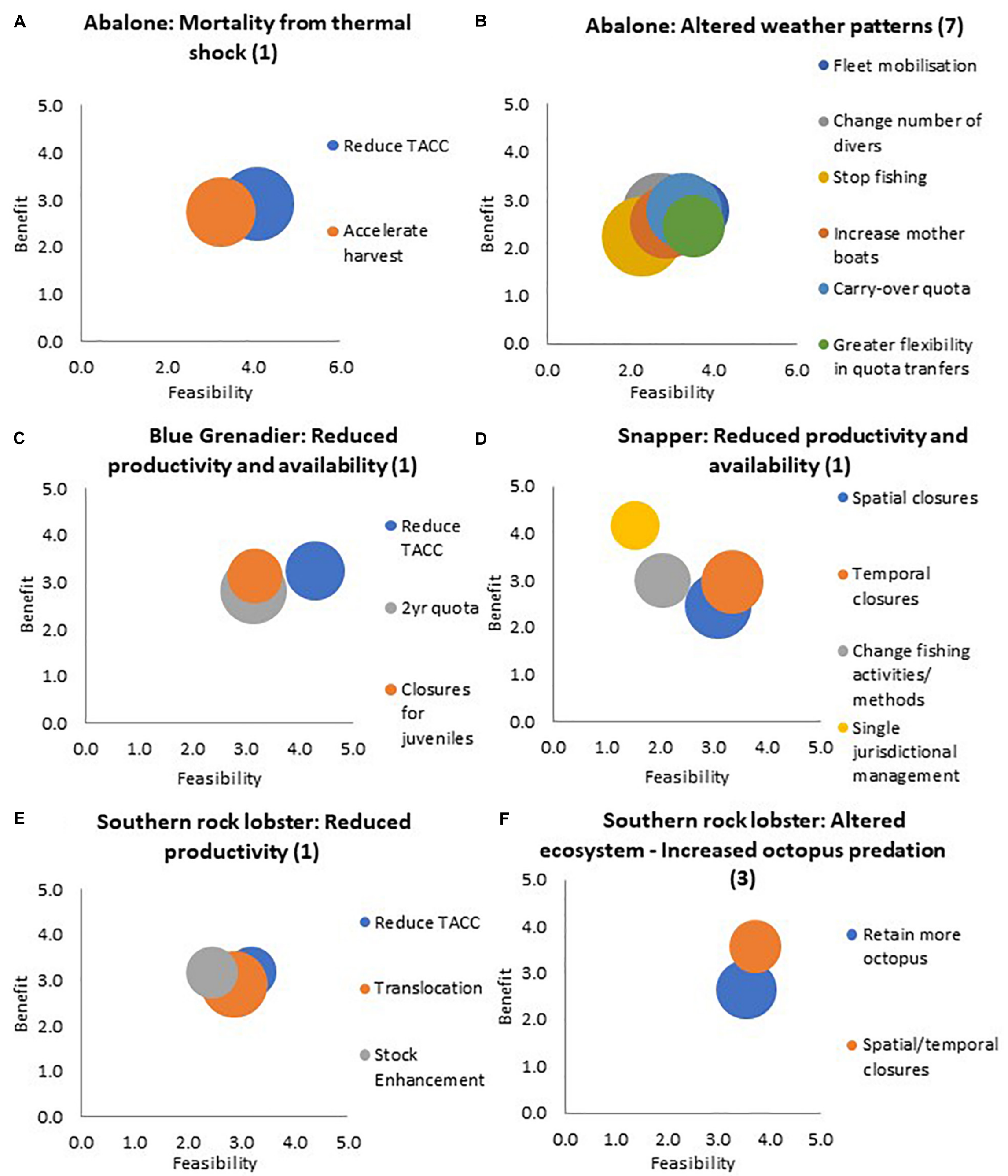

FIGURE 3 | Evaluation scores for level of expected benefit, feasibility, and risk of selected adaptation options addressing specific climate challenges for abalone **(A,B)**, blue grenadier **(C)**, snapper **(D)**, and southern rock lobster fisheries **(E,F)** in south-eastern Australia. The size of the bubble reflects the level of risk. The number in brackets refers to the broad challenge from the respective tables.

DISCUSSION

The nature and effectiveness of adaptation planning is strongly affected by the analytical approach to generating decision support to inform adaptation choices and coordination (Wise et al., 2014) and the evidence base for the system in question. Existing evaluative techniques are unlikely to be sufficient to support planning of optimal adaptation outcomes on their own. Qualitative assessments of adaptation options based on normative criteria are subject to participant biases and do not parameterize the technical effectiveness or efficiency of alternative options and this limits their value in assessing impact (Choy, 2014; Miles et al., 2014). Quantitative techniques, such as MSE, have high data requirements, presume linear cause-and-effect relationships and high certainty regarding management objectives and can therefore be less suitable for planning processes seeking to identify inter-temporal adaptation pathways (Haasnoot et al., 2013; Wise et al., 2014).

The semi-quantitative "first pass" screening method demonstrated in this paper was effective in distinguishing and comparing adaptation options for and across the four case study fisheries. The options ranged from those intended to decrease exposure of the fish stock to climate driven effects on productivity (for example, translocation and stock enhancement of southern rock lobster) to those designed to increase adaptative capacity/resilience of the stock (e.g., reduce the TACC) and socio-economic resilience of the fishing fleet (e.g., extending quota catching periods). The range of adaptation responses and implementation approaches that stakeholders revealed in the study reinforces the need for step-wise, structured and mixed-method techniques to support adaptation planning and coordination. The screening method demonstrated is not mutually exclusive of other established evaluative techniques as required by the complex and dynamic decision-making contexts confronted by fisheries management. For example, a semi-quantitative criteria-based assessment of a range of adaptation options could be used to select a smaller set of options for subsequent MSE, cost benefit analysis, impact assessment or equivalent evaluative analysis as required (e.g., Hobday et al., 2011).

Diversity of Adaptation Response Options and Adaptation Preferences

The options characterized for each fishery were found to vary in degree of adaptation (from autonomous to transformative), the lead and consequence period, and the type of stakeholder leading implementation (i.e., public, private and multi stakeholder). Implementation of a diversity of types of collective action at different levels and scales is more likely to engender a full array of climate adaptive properties necessary to sustain fisheries activity, notwithstanding potential maladaptation (Adger et al., 2005; Hobday et al., 2016; Ogier et al., 2016).

The study tested a method of screening a broad range of adaptation response options by characterizing options with reference to their attributes for addressing specific climate challenges, followed by semi-quantitative formative evaluation of options to enable comparison. However, comparison of the evaluation of all options was limited by the low levels of participation in the evaluation exercise by all groups. Only those options for which minimum required numbers of industry, management, and research stakeholders participated in the exercise are presented in this study. This limitation could be addressed in future applications to support more comprehensive comparison of the full range of options.

The sub-set of options evaluated were primarily those intended to adapt to changing productivity or availability of the stocks via a variety of mechanisms, inclusive of conventional fisheries input, and output controls applied to fishing catch and effort (such as TACC reductions, temporal or seasonal closures) through to quota system administration, early harvesting in the event of expected high heatwave-induced mortality, and stock enhancement. Reduction of the total annual commercial catch as well as reductions in both effort and catch through spatial and temporal closures were the options scored as having the highest level of expected benefit and of feasibility and the lowest level of risk of negative outcomes overall by management and research participants in the study. Industry participants scored these options lower in terms of level of feasibility and expected benefit overall in comparison to management and research participants, although the differences were low in degree. However, the limited range of scores for level of risk of negative outcomes across all groups and across all options indicates the need to increase the sensitivity of this evaluative criteria to support greater delineation and comparison of the level of risk posed by alternate options.

Participatory Evaluation and Its Limitations

Participation in the evaluation exercise by fisheries managers, research scientists, and representatives of industry allowed for *in situ* operational and local ecological knowledge of fishers to be considered alongside science-based evidence and model-based predictions. It further enabled measurement of the degree of consensus and level of potential conflict between stakeholders in the evaluation of adaptation options. For the majority of the adaptation options evaluated for the abalone fishery, industry members ranked benefit, and feasibility lower than management and research agency participants. This may have reflected industry members' skepticism of management agency-led adaptation options, or of the likelihood of any private benefit being generated. In contrast, industry members of the rock lobster fishery perceived higher levels of expected benefit arising from translocation and stock enhancement options, compared to management and research agency participants. These differences may highlight asymmetries in information, differences in risk tolerance or preferences for specific types of benefits (Nursey-Bray et al., 2012; Van Putten et al., 2015). In both fisheries, low levels of consensus highlight differences warranting further exploration and discussion. Analysis of the scores given for individual measurement criteria for feasibility, risk and expected benefit would support this.

The formative influence which participatory processes provide to participating stakeholders introduces a source of bias. The initial characterization of climate challenges and response options and the preferences and positions expressed in deliberative processes can determine the framing of adaptation possibilities (Haasnoot et al., 2013; Wise et al., 2014). In this study the small number of participants from each of the stakeholder groups (see **Table 4**) increased the likelihood of sample bias (Berk, 1983). In some cases, the small number of participants reflected the level of consolidation in the fishery – the blue grenadier fishery is managed under a single jurisdiction and the majority of catch is taken by a small number of large operators. In contrast, the snapper fishery is managed under multiple jurisdictions. The large numbers of commercial and recreational fishers that participate in this fishery would ideally necessitate a larger

TABLE 4 | Evaluation score classes and level of consensus within stakeholder group for selected adaptation options for abalone, blue grenadier, snapper, and southern rock lobster in south-eastern Australia.

Fishery	Climate challenge	Adaptation option	Stakeholder group	No. responses	Mean evaluation score classification			*Level of consensus within stakeholder group*		
					Feasibility	**Risk**	**Benefit**	***Feasibility***	***Risk***	***Benefit***
Abalone	1. Mortality event through thermal shock (extreme event)	1a. Reduce the TACC by up to 40%	Industry	3	Moderate	Moderate	Low	*High*	*High*	*Low*
			Management	3	Moderate	Low	Moderate	*Low*	*High*	*High*
			Research	3	High	Low	Low	*High*	*High*	*High*
			All (combined)	9	High	Low	Low	*High*	*High*	*High*
		1c. Bring harvest forward when forecast	Industry	4	Low	Moderate	Low	*Medium*	*Medium*	*High*
			Management	3	Moderate	Very low	Moderate	*Medium*	*High*	*Low*
			Research	3	Moderate	Low	Low	*Low*	*High*	*High*
			All (combined)	10	Moderate	Low	Low	*Low*	*Medium*	*High*
	7. Altered weather patterns	7a. Fleet mobilization – prioritizing fishing trips/areas	Industry	4	Low	Low	Low	*Medium*	*High*	*Medium*
			Management	3	Moderate	Low	Low	*High*	*High*	*High*
			Research	3	High	Very low	Moderate	*High*	*High*	*High*
			All (combined)	10	Moderate	Very low	Low	*High*	*High*	*High*
		7b. Increase use of mother boats	Industry	4	Very low	Low	Low	*Medium*	*High*	*Medium*
			Management	3	Moderate	Low	Low	*Low*	*High*	*High*
			Research	4	Moderate	Low	Low	*High*	*High*	*High*
			All (combined)	11	Low	Low	Low	*Low*	*High*	*High*
		7c. Change number of divers	Industry	4	Low	Low	Low	*High*	*High*	*Medium*
			Management	3	Low	Low	Low	*High*	*High*	*High*
			Research	3	Moderate	Very low	Low	*High*	*High*	*High*
			All (combined)	10	Low	Low	Low	*High*	*High*	*High*
		7d. Stop fishing to increase biomass & CPUE	Industry	3	Low	Moderate	Low	*High*	*High*	*High*
			Management	2	Very low	Low	Low	*High*	*Low*	*High*
			Research	2	Low	Low	Low	*High*	*High*	*High*
			All (combined)	7	Low	Low	Low	*High*	*High*	*High*
		7e. Carry quota across years	Industry	4	Low	Low	Low	*Low*	*High*	*Low*
			Management	3	Moderate	Low	Moderate	*High*	*High*	*High*
			Research	5	Moderate	Low	Moderate	*High*	*High*	*High*
			All (combined)	12	Moderate	Low	Low	*Medium*	*High*	*High*
		7f. Greater flexibility in quota transfers	Industry	3	Low	Low	Low	*High*	*Medium*	*High*
			Management	2	High	Very low	Low	*High*	*High*	*High*
			Research	2	Moderate	Low	Low	*High*	*High*	*High*
			All (combined)	7	Moderate	Low	Low	*High*	*High*	*High*
Blue grenadier	1. Reduced productivity/ availability	1a. Reduce TACC by up to 40%	Industry	3	Moderate	Low	Moderate	*High*	*High*	*High*
			Management	2	High	Low	Moderate	*High*	*High*	*High*
			Research	7	High	Low	Moderate	*High*	*High*	*High*
			All (combined)	12	High	Low	Moderate	*High*	*High*	*High*

(Continued)

TABLE 4 | Continued

Fishery	Climate challenge	Adaptation option	Stakeholder group	No. responses	Mean evaluation score classification			*Level of consensus within stakeholder group*		
					Feasibility	Risk	Benefit	*Feasibility*	*Risk*	*Benefit*
		1f. Spatial or temporal closures for juveniles	Industry	3	Low	Low	Moderate	*High*	*High*	*High*
			Management	1	Moderate	Very low	Low	*High*	*High*	*High*
			Research	5	Low	Low	Moderate	*High*	*High*	*High*
			All (combined)	9	Moderate	Low	Moderate	*High*	*High*	*High*
		1g. 2 years quota period	Industry	3	Moderate	Low	Moderate	*High*	*High*	*High*
			Management	1	Moderate	Moderate	Very low	*High*	*High*	*High*
			Research	6	Moderate	Low	Low	*High*	*High*	*High*
			All (combined)	10	Moderate	Low	Low	*High*	*High*	*High*
Snapper	1. Reduced productivity and availability	1a. Reduce effort through spatial closures	Industry	3	Low	Moderate	Low	*High*	*Low*	*High*
			Management	2	Moderate	Low	Low	*High*	*High*	*Low*
			Research	4	Low	Moderate	Low	*Medium*	*Medium*	*Medium*
			All (combined)	9	Moderate	Moderate	Low	*Low*	*Low*	*Medium*
		1b. Reduce effort though temporal closures	Industry	3	Low	Moderate	Moderate	*Low*	*High*	*Medium*
			Management	2	Moderate	Low	Low	*Low*	*High*	*Low*
			Research	4	Moderate	Low	Moderate	*Medium*	*Medium*	*Medium*
			All (combined)	9	Moderate	Low	Low	*Low*	*Medium*	*Low*
		1d. Change seasonal fishing activities/ methods	Industry	3	Low	Low	Moderate	*High*	*High*	*High*
			Management	2	Low	Low	Moderate	*High*	*High*	*High*
			Research	4	Very low	Low	Low	*High*	*Medium*	*Medium*
			All (combined)	9	Low	Low	Moderate	*High*	*Medium*	*Medium*
		1e. Implement single cross-jurisdictional management arrangements across stock range	Industry	3	Very low	Low	Moderate	*High*	*Low*	*Low*
			Management	2	Very low	Low	High	*High*	*Low*	*High*
			Research	4	Very low	Very low	High	*Medium*	*High*	*Medium*
			All (combined)	9	Very low	Low	High	*High*	*Medium*	*Medium*
Southern rock lobster	1. Reduced productivity	1a. Reduce TACC by up to 40%	Industry	7	Moderate	Low	Low	*Medium*	*Medium*	*High*
			Management	4	Moderate	Low	Moderate	*High*	*High*	*High*
			Research	6	Low	Very low	Moderate	*High*	*Medium*	*High*
			All (combined)	17	Moderate	Low	Moderate	*High*	*Medium*	*Medium*
		1f. Translocation	Industry	3	Low	High	High	*High*	*High*	*Low*
			Management	1	Low	Low	Low	*High*	*High*	*High*
			Research	3	Low	Low	Low	*Medium*	*Medium*	*Low*
			All (combined)	7	Low	Moderate	Low	*Medium*	*High*	*Medium*

(Continued)

TABLE 4 | Continued

Fishery	Climate challenge	Adaptation option	Stakeholder group	No. responses	Mean evaluation score classification			Level of consensus within stakeholder group		
					Feasibility	Risk	Benefit	*Feasibility*	*Risk*	*Benefit*
		1e. Stock enhancement	Industry	5	Moderate	Very low	Moderate	*High*	*High*	*High*
			Management	4	Very low	Moderate	Low	*High*	*Medium*	*Medium*
			Research	6	Low	Low	Low	*Low*	*Low*	*Low*
			All (combined)	15	Low	Low	Moderate	*High*	*Medium*	*Medium*
	3. Altered ecosystem – Increased octopus predation	3a. Spatial and temporal closures	Industry	5	Moderate	Moderate	Moderate	*High*	*Low*	*High*
			Management	3	Moderate	Low	Moderate	*Low*	*High*	*High*
			Research	3	Moderate	Very low	Moderate	*High*	*High*	*High*
			All (combined)	11	Moderate	Low	Moderate	*High*	*High*	*High*
		3b. Increase take of octopus	Industry	0	N/a	N/a	N/a	*N/a*	*N/a*	*N/a*
			Management	4	Moderate	Low	Low	*High*	*Medium*	*Medium*
			Research	3	Moderate	Low	Moderate	*High*	*High*	*High*
			All (combined)	7	Moderate	Low	Low	*Medium*	*Medium*	*Medium*

number of survey respondents from the various jurisdictions, and also from the recreational sector, than the number who participated in this study.

Incorporation of Inter-Temporal Characteristics and Dynamic Adaptation Pathways

Temporal dimensions of the implementation and consequence of identified adaptation options were included in the characterization matrix. The extent to which an option also addressed other climate challenges facing that fishery was also included. However, together these characteristics did not address the inter-temporal properties of identified adaptation options, that is, the extent to which an option would affect what options would become available in the future (Wise et al., 2014). Examples of options which would have clear inter-temporal implications include options to change location of fishing operations or fishing gears used (snapper), or establishment of new managed fisheries (snapper) or of new products and markets (blue grenadier). Nor did the characterization matrix account for interactions between options if implemented at the same time, or for incorporating feedbacks which would require adjustment of both the characterization and comparative evaluation of options. These limitations together highlight the need for characterization and evaluation which supports dynamic adaptation pathways, or the sequencing of sets of possible adaptation actions "based on alternative external developments over time" (Haasnoot et al., 2013) in preference to the focus of this study on single options using static models of anticipated impact. However, the rapid assessment techniques applied in this study have the advantage of being repeatable with low resourcing requirements and so could be adapted to periodically re-evaluate the sequencing of sets of possible adaptations as the effects of previous adaptation responses are observed.

Integration Into Fisheries Planning and Management

The results of the evaluations have the potential to inform the further prioritization of options for more quantitative impact assessment, or MSE against management objectives, as required by public management agencies when considering changes to fisheries management settings (Grafton, 2010; Jennings et al., 2016). This potential would be strengthened by including further characteristics in the characterization matrix concerning the extent to which implementation of the adaptation option would be through existing or new management instruments. In addition, the specific evaluation criteria could be more closely aligned with any relevant management objectives or policy-based evaluative criteria.

The rapid assessment procedures and evaluative techniques applied in this study also have the potential to function as pre-feasibility assessments for industry stakeholders when prioritizing options for private sector adaptation strategies. The inclusive design of the study further supports improved awareness of industry-led adaptation responses and strategies and therefore, potentially, better coordination between public

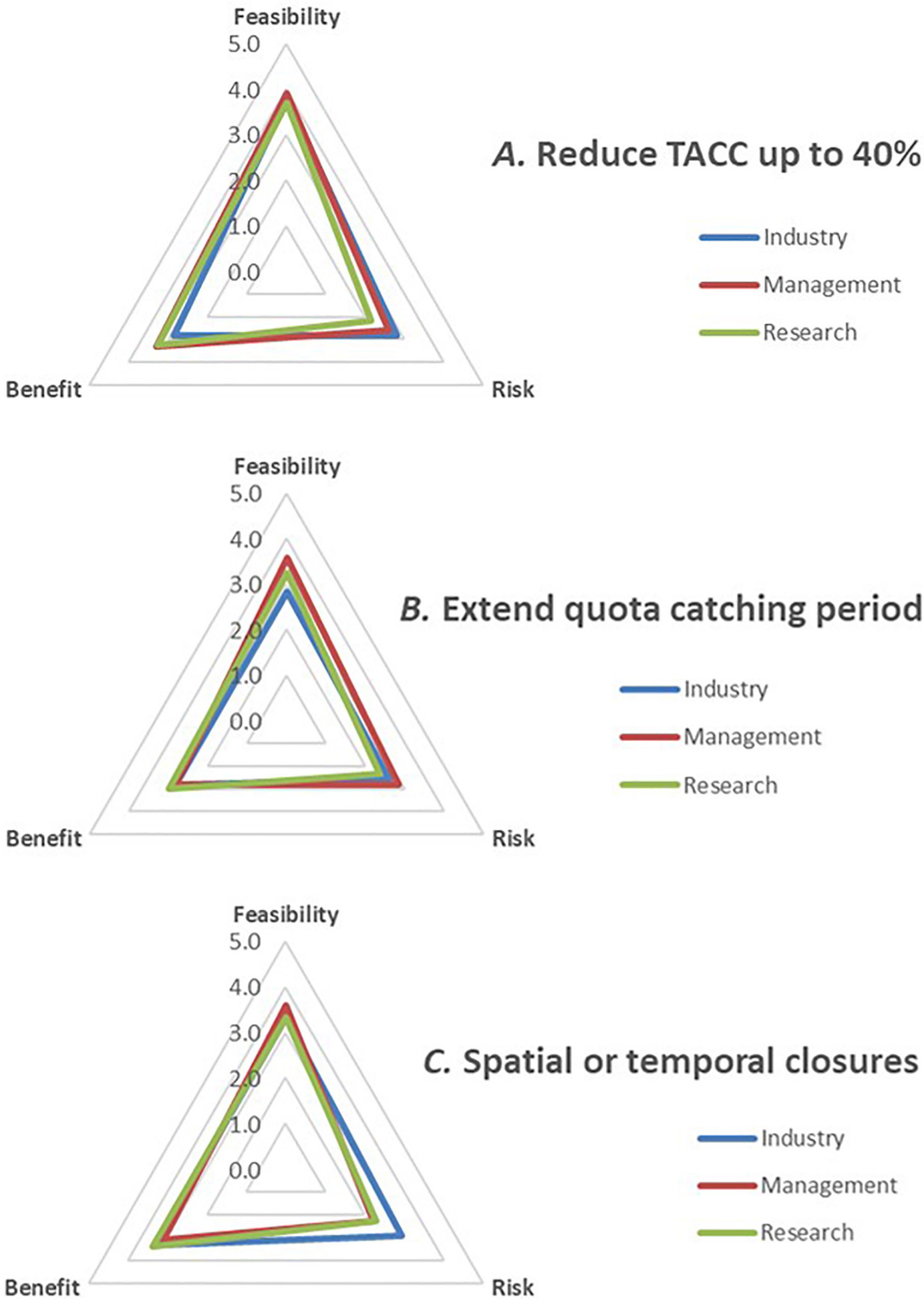

FIGURE 4 | Comparison of the evaluation by industry, management and research respondents of feasibility, risk, and benefit of three common adaptation options: Reduce TACC **(A)**; Extend quota catching period **(B)**; and Spatial or temporal closures **(C)**.

and private sector responses (Tompkins and Eakin, 2012; Gutiérrez and Morgan, 2017).

The additional planning sub-processes developed and tested in this study are directly relatable to existing fisheries adaptative management processes (Grafton, 2010; Lindegren and Brander, 2018) and could be incorporated into the initial impact pathway characterization and risk assessment stages of integrated ecosystem assessment exercises. Currently there is no formal requirement for public management agencies to undertake any type of climate adaptation planning (Creighton et al., 2015), so uptake of results or planning sub-processes is at the discretion of fisheries managers and industry representatives.

CONCLUSION

Adaptation planning in response to the increasing vulnerability of targeted fish stocks and affected communities to climate driven effects requires a range of analytical techniques to support decision making. Planning requires making choices between options that vary in degree of adaptation, level of private and public sector dependency, and inter-temporal effects in order to optimize outcomes. This study has demonstrated a two-step "first pass" rapid assessment screening technique in which 100 adaptation options for four fisheries in south-eastern Australia were characterized by the specific climate challenge they addressed, and the attributes of their implementation and consequence. Semi-quantitative evaluation of a selected sub-set options was effective in distinguishing between options on the basis of perceived level of feasibility, risk of negative effects, and expected benefit in responding to a specific climate challenge. Levels of consensus between scientists, fisheries managers, and industry representatives in evaluative scores was inversely related to the degree of adaptation proposed by an option. Managers and research staff preferred the significant reduction of total allowable commercial catches as an option as revealed by higher scores for the level of expected benefits compared with industry respondents. Benefits of this technique, therefore, include identification of – not only – differing preferences by stakeholder groups, but also of the basis of these differences. This function, in turn, supports identification and, potentially, resolution of points of conflict. While the techniques applied in this study were able to demonstrate the utility of "first pass" low-cost techniques, incorporation of further steps to identify and evaluate the implications of inter-temporal and distributional effects of implementing adaptation options is required.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

EO led the drafting of the manuscript. GP, SJ, PH, SF, SM, and AH contributed to the manuscript's development. EO, SJ, GP, AS, AH, and SF designed the characterization and evaluation methods. CM, PH, SM, TW, GT, AF, CG, AL, and AS contributed to the refinement of these methods. EO and AS undertook data collection and analysis. GP led the overall research project funded by the Fisheries Research and Development Organization (FRDC) on behalf of the Australian Government (grant number 2011/039), of which the results of this study are a part. GP led the project to assess key effects of climate change for the four species, results of which were used in this study. CM, PH, SM, TW, GT, AH, CG, SF, AF, and AL contributed to that assessment.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00097/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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